Title

Assessing the effects of technological progress on energy efficiency in the construction industry: A case of China

Authors
Zhu, W
Zhang, Z
Li, X
et al.

Publication Date
2019-11-20

DOI
10.1016/j.jclepro.2019.117908

Peer reviewed

Journal of Cleaner Production 238 (2019) 117908

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Assessing the effects of technological progress on energy efficiency in the construction industry: A case of China

Weina Zhu [a], Zhihui Zhang [a], Xiaodong Li [a, *], Wei Feng [b], Jifeng Li [c]

[a] Dept. of Construction Management, School of Civil Engineering, Tsinghua Univ., Beijing, 100084, China
[b] Energy Analysis and Environmental Impacts Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90R2002, Berkeley, CA, 94720, United States
[c] State Information Center, No. 58 Sanlihe Road, Xicheng District, Beijing, 100045, China

A R T I C L E I N F O

Article history:
Received 6 April 2019
Received in revised form
29 July 2019
Accepted 2 August 2019
Available online 3 August 2019

Handling editor is Sandro Nizetic

Keywords:
Energy efficiency
Production function
Technological progress
Construction industry

A B S T R A C T

Energy-saving technologies in buildings have received great attention from energy efficiency researchers in the construction sector. Traditional research tends to focus on the energy used during building operation and in construction materials production, but it usually neglects the energy consumed in the building construction process. Very few studies have explored the impacts of technological progress on energy efficiency in the construction industry. This paper presents a model of the building construction process based on Cobb-Douglas production function. The model estimates the effects of technological progress on energy efficiency with the objective to examine the role that technological progress plays in energy savings in China's construction industry. The modeling results indicated that technological progress improved energy efficiency by an average of 7.1% per year from 1997 to 2014. Furthermore, three main technological progress factors (the efficiency of machinery and equipment, the proportion change of the energy structure, and research and development investment) were selected to analyze their effects on energy efficiency improvement. These positive effects were verified, and results show the effects of first two factors are significant. Finally, recommendations for promoting energy efficiency in the construction industry are proposed.

1. Introduction

Energy is generally regarded as a vital factor of production in various sectors (Zha and Zhou, 2014). Due to increasing environmental problems and energy security issues, exploring energy efficiency and energy intensity in high energy-consuming industries has become a dominant topic worldwide. “Energy efficiency” is often used as a generic term that refers to approaches or technologies that use less energy to produce the same amount of services or useful output (Patterson, 1996). The International Energy Agency (IEA) defines energy efficiency as “a way of managing and restraining the growth in energy consumption.” On the other hand, energy intensity (namely, energy consumption per unit of GDP) is a binding target for national economic and social development (Chen et al., 2019), and it provides indirect evidence for formulating targeted energy efficiency policy, especially at the technological and engineering levels (Proskuryakova and Kovalev, 2015). Energy intensity data were used as a generalized integral measure of long-term feedback to energy efficiency. Generally, energy efficiency is the reciprocal of energy intensity (Li and Lin, 2014; Voigt et al., 2014). As shown in Fig. 1, the first three high energy-consuming sectors in China over 18 years are the manufacturing industry (MI), household energy consumption (HEC) (mainly from the building operation's energy consumption), and transportation industry (TI). Many energy efficiency research studies related to those three sectors have been conducted (Xu and Lin, 2016; Zha et al., 2017).

Some industries are usually neglected due to their small ratio of energy consumption; for example, the construction industry (CI). However, energy demand in the construction industry is likely to increase significantly. China is undergoing rapid industrialization and urbanization (Wang et al., 2014), and substantial energy demands continue to exist in different sectors. Fig. 2 illustrates the growth rates of nine industries' energy consumption in China from 1997 to 2014.[1] During that time, the construction industry showed

* Corresponding author.
E-mail address: eastdawn@tsinghua.edu.cn (X. Li).

[1] The division standards are based on the National Industry Classification (GB/T 4754–2011) in China.

https://doi.org/10.1016/j.jclepro.2019.117908

Nomenclature list

AFAFI	agriculture, forestry, animal husbandry and fishery industry
CDPF	Cobb-Douglas production function
CI	construction industry
CIE	construction and installation engineering
CTBUH	Tall Buildings and Urban Habitat
EC	energy consumption
EGWSI	electricity, gas and water production supply industry
EI	extractive industry
EN	employment number
GDP	gross domestic product
HEC	household energy consumption
IEA	International Energy Agency
IFA	investment of fixed assets
MI	manufacturing industry
MOHURD	Ministry of Housing and Urban-Rural Development of the People's Republic of China
NVFA	net values of fixed assets
TI	transportation industry
TOV	total output value
WRI	wholesale and retail industry

the fastest average annual growth rate (9.78%). That means that construction of a large number of new buildings consumes a great deal of energy in the construction industry every year. According to Qiu Baoxing, the China's vice-minister of construction, an annual addition of 1.5 billion to 2 billion square meters (m^2) of new building stock is probable in China (Fernández, 2007). In addition, tall buildings are being constructed in China, accompanied by massive energy consumption from high energy-consuming machinery and equipment. According to the report on Tall Trends of 2018 from the Council on Tall Buildings and Urban Habitat (Skyscrapercenter, 2018), China recorded 88 completions of Tall Buildings, the most by a single country (Skyscrapercenter, 2018).

From the perspective of building life-cycle energy use, Fig. 3 illustrates the energy use scopes in the construction sector. Total life-cycle energy use is the sum of life-cycle embodied energy and operating energy. The operating energy is conventionally found to be greater than a building's total life-cycle embodied energy (e.g., 54%–98% and 2%–46%, respectively) (Azari and Abbasabadi, 2018). However, as buildings have become increasingly energy efficient, and as even net-zero energy buildings emerge, the share of embodied energy is expected to increase (Zeng and Chini, 2017).

Embodied energy is relatively complex. It is composed of the initial embodied energy, recurrent embodied energy, and demolition energy, as shown in Fig. 3. The initial embodied energy is the total energy used to extract raw materials, manufacture and transport products and components, and construct a building. Furthermore, it has two components—direct and indirect energy consumption (Ibn-Mohammed et al., 2013). Direct energy is the energy associated with constructing the building and transporting building components on the site. In other words, it is the energy related to various on-site operations like construction, transportation, and administration. Indirect energy is the energy used to acquire, process, and manufacture the building materials. Malmqvist et al. (2018) concluded that embodied energy of the construction stage varies between 6% and 38% of the total embodied energy, as shown in Fig. 3. Due to the much smaller proportion of life-cycle embodied energy and the data availability issues, research on the direct energy consumption on the construction site is often easily neglected (Liu and Lin, 2016; Malmqvist et al., 2018).

To sum up, as the shares of embodied energy are expected to increase (Dimoudi and Tompa, 2008) and China is undergoing rapid industrialization and urbanization, the energy consumption of the building production process is becoming an important research issue. However, energy consumption in the construction industry is often neglected and has few studies. Therefore, to bridge the research gap, this study focused on energy consumption in the construction industry, using national statistical data.

Reducing the growth rate of energy consumption can be achieved by improving energy efficiency (Huang et al., 2017b). Improvements in energy efficiency has considerably slowed energy consumption growth (Fisher-Vanden et al., 2004). However, energy efficiency can be determined by different variables (e.g., the energy consumption structures, the price of energy, technological

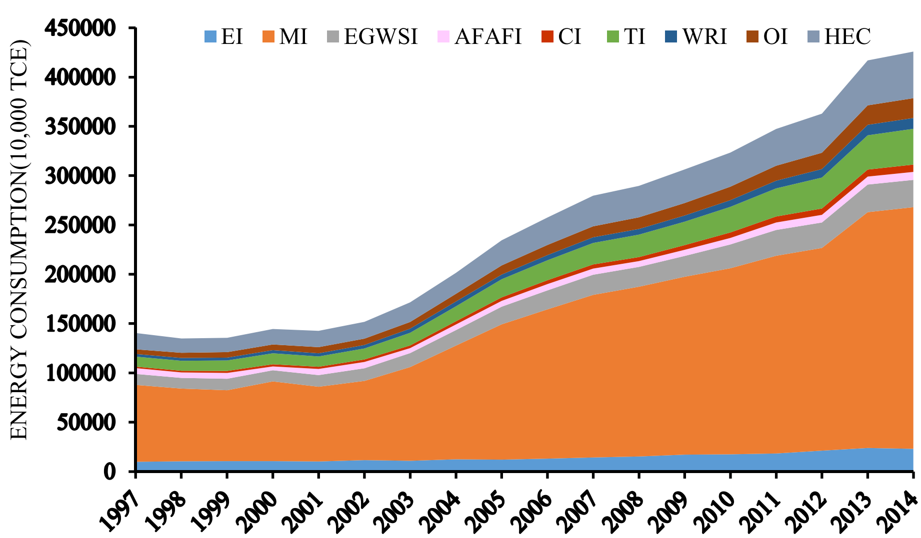

Fig. 1. Energy consumption of nine industries.
Notes: EI: extractive industry, MI: manufacturing industry, EGWSI: electricity, gas and water production supply industry, AFAFI: agriculture, forestry, animal husbandry and fishery industry, CI: construction industry, TI: transportation industry, WRI: wholesale & retail industry, OI: other industry, HEC: household energy consumption.

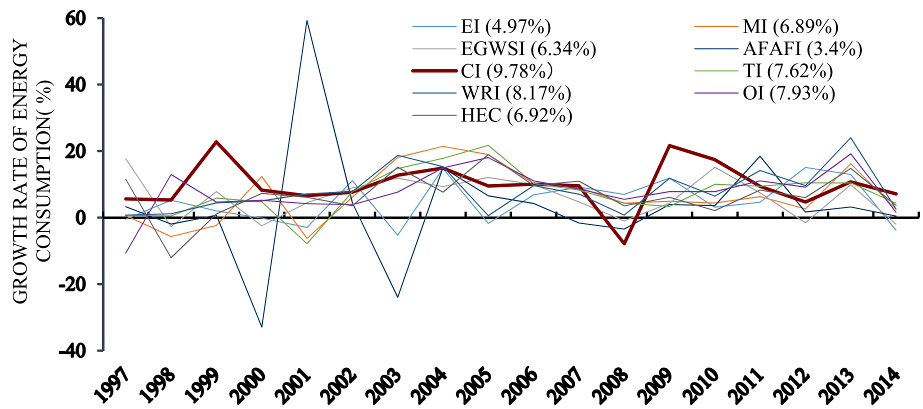

Fig. 2. Growth rates of the energy consumption in nine industries.
Notes: EI: extractive industry, MI: manufacturing industry, EGWSI: electricity, gas and water production supply industry, AFAFI: agriculture, forestry, animal husbandry and fishery industry, CI: construction industry, TI: transportation industry, WRI: wholesale & retail industry, OI: other industry, HEC: household energy consumption. The percentages in parentheses indicate the average annual growth rate.

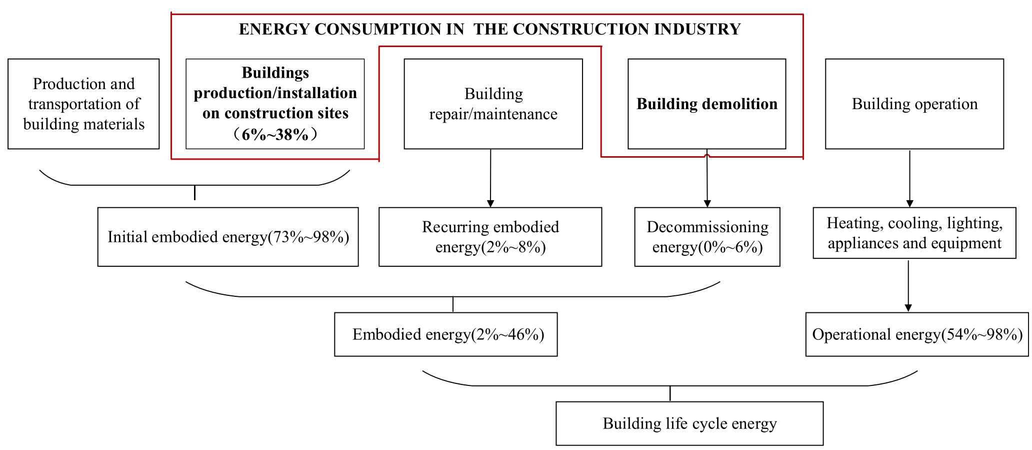

Fig. 3. Energy consumed in the building production process.
Sources: Azari and Abbasabadi (2018), Dixit (2017, 2019), and Malmqvist et al. (2018).

progress). Specifically, energy efficiency improvements result from ongoing technological progress, response to rising energy prices, and competitive forces to cut costs. More important, some research has shown that technological progress has a stronger impact on energy efficiency than other factors do (Huang et al., 2017a). Huang et al. (2018) examined the effects of technological progress (including indigenous and foreign innovation) on energy intensity in China. In practice, one of the most common relationships between energy efficiency and technological progress is the government's energy saving policies. These policies generally rely on using technological progress to achieve energy savings because technological progress is an effective means by which to improve energy efficiency (Appendix A). As a consequence, exploring the impacts of technological progress on energy efficiency in the construction industry can be an effective and reliable measure for reducing embodied energy in the industry (Lin and Liu, 2015a; Noailly, 2012).

This study focused on the impacts of technological progress on energy efficiency in the construction industry from the perspective of the building production process, which is analogous to the industrial product production process. The construction company is the manufacturer of building products, and the production of those products occurs on the construction sites. The construction company's energy consumption is mainly from the machines and equipment on sites (trucks, loaders, cranes, pumping and welding machines, etc.), offices and living at the construction site (lighting, cooking, heating, cooling, etc.), and some experiments and maintenance.

The remainder of this paper is organized as follows. A review of the literature is provided in Section 2, and the methodology is introduced in Section 3. In Section 4, the results and discussions are presented, and the conclusions are reported in Section 5.

2. Literature review

Economic data for the last two centuries have demonstrated the presence of a self-sustaining mechanism of cumulative productivity growth known as technological progress or technological change. In mathematical economics, technological progress refers to a combination of all effects that lead to increased production output without increasing the amounts of the productive inputs (e.g., capital, labor, and resources) (Hritonenko and Yatsenko, 2013). As for the measurement of technological change, various variables have been employed, such as total factor productivity (TFP) index (Li et al., 2013), energy efficiency (Xu and Lin, 2016), differences between output growth and input growth (Dasgupta and Roy, 2015), productivity gains (Aguilera and Ripple, 2012), patents

(Albino et al., 2014; Li and Lin, 2017), research and development (R&D) investments (Lin and Zhang, 2013), and financial development and foreign direct investment (Li and Lin, 2017). Investigating the effects of technological progress on energy consumption has gained great attention, and the growing body of literature can be divided into the two main categories.

First, numerous studies have focused on the impacts of technological progress on energy consumption in the industrial sector. Dasgupta and Roy (2015) considered technological progress to be one of the key drivers of energy demand in India's manufacturing industry, and results from their study indicated that productivity growth of energy input was induced by both technological progress and an increase in energy price. Karali et al. (2017) incorporated technological learning into energy models in the iron and steel sector to investigate the potential for energy savings and emission reductions; their results demonstrated that the total energy consumption of the iron and steel sectors in the United States is expected to decrease by 13% (180 PJ) in 2050 as a result of technological learning. Ouyang and Lin (2015) used the ratio of scientific R&D spending to the total sales revenue in the Chinese building materials industry as an indicator of technological progress in that sector, and the results showed that technological progress ensures the continuous improvement of the sectoral energy efficiency.

However, a general consensus has been reached that there exists a rebound effect[2] with regard to the effects of technological progress on energy efficiency. Bentzen (2004) found that the direct rebound effect resulting from technological progress in the U.S. manufacturing sector was 24%, implying that technological progress in that sector achieves only approximately 76% of its energy saving target due to the rebound effect. In addition, Lin and Li (2014) measured the direct rebound effect in China's heavy industry during 1980–2011 to be 74.3%, and Lin and Tian (2016) found that the direct rebound effect in China's light industry was approximately 37.7% during 1980–2012. Furthermore, Li et al. (2016) developed an improved estimation model for the energy rebound effect induced by technological progress; the results showed that the energy rebound effect of 36 industrial sectors in China during 1998–2011 was 88.42%.

Second, a large number of studies have explored energy-saving technologies in the construction sector. For instance, Geng et al. (2015) created a framework for assessing the suitability of energy-saving technologies in buildings, and 20 energy-saving technologies for office buildings were selected, to assess their energy-saving potential. Menyhart and Krarti (2017) evaluated the potential energy savings of dynamic insulation materials (DIMs) for residential buildings in the United States; their results revealed that DIM technology could achieve total energy savings ranging from 7% to 42%. Moreover, Zhao et al. (2018) developed a portable thermoelectric energy conversion unit to explore its potential to reduce the energy consumption of a building using personal thermal management techniques. Cannavale et al. (2017) carried out simulations based on an existing office building in Italy and analyzed the potential energy savings of integrating innovative photovoltaic technologies.

The rebound effect was also explored in the construction sector. Liu and Lin (2016) calculated the energy rebound effect to be 21.8% in China's construction industry, and their research results indicated that technological advancement achieves roughly 78.2% of its energy conservation target due to the rebound effect. Lin and Liu (2015b) considered that although the rebound effect offset some anticipated energy conservation, the rebound magnitude for the construction industry is relatively small compared to other sectors. Grossmann et al. (2016) developed an interdisciplinary method to estimate the rebound effects of office buildings in Germany. The results showed technical upgrade measures were successful in these buildings. Therefore, technological advancement is still an effective way to improve energy efficiency in order to conserve energy in the construction industry.

The aforementioned studies demonstrated that, both in the industrial sector and in the construction sector, technological progress has improved energy efficiency, but also that it can lead to rebound effects. Nevertheless, some research gaps require further investigation.

The contributions of this study include the following:

- Because the energy consumption in the construction industry is a relatively small portion of embodied energy, this part of energy consumption is easily neglected. Thus, the statistical and analytical research on the energy efficiency in the construction industry has lacked sufficient exploration. This study used the national statistical data of the construction industry to explore the energy efficiency of the building production process.
- Although some studies have demonstrated the effects of technological progress on energy efficiency in the production process of industrial products (e.g., iron, steel, building materials), few studies have explored the influence of technological progress on energy efficiency in the construction industry from the perspective of the building production process. This study adopted the production function to simulate the effects of technological progress on the energy efficiency in the construction industry.
- Three technological progress factors were further analyzed to explain their roles in improving energy efficiency in construction.

3. Method and models

3.1. Research design

3.1.1. Cobb-Douglas production function (CDPF)

Technology is commonly described through the relationship between inputs and outputs in general equilibrium within top-down models. In economics, the CDPF is widely used to represent the relationship between product outputs and resource inputs (e.g., capital and labor). Hence, this function has been used widely in research on technological progress (Sircar and Choi, 2009). The application of this function is involved mainly in the industrial production field for a firm, sector, or industry in a country or region, and it has been used for almost 100 years (Hu and Hu, 2013). In addition, the CDPF has been employed to explore the role that technological progress plays in energy consumption (Hatirli et al., 2005; Rafiee et al., 2010). One possible reason that the CDPF is often selected to estimate the relationship between resource inputs and product outputs could be the accurate statistical significance and expected parameter signs of its estimates (Mobtaker et al., 2010). For the construction industry, the CDPF can also properly represent the real industrial production process of building products.

The original CDPF had the following form:

[2] Rebound effect is usually defined that technological progress could improve energy efficiency and save energy, but improvements in energy efficiency will also reduce the unit cost of production and price. Thus, it caused the growth in product demand to increase energy consumption, and finally the savings derived from energy efficiency improvements are partially offset by the extra energy consumption.

$$Q = A*K^{\alpha}*L^{\beta} \tag{1}$$

Subsequently, an energy element was added to the formula, and that has been applied in the energy field for many years:

$$Q = A*K^{\alpha}*L^{\beta}*E^{\gamma} \tag{2}$$

where Q denotes the total production (the monetary value of all goods produced); A denotes technological progress; K represents the capital input (the monetary worth of all machinery, equipment, and buildings, etc.); L signifies the labor input (the total number of persons); E is the energy input (the total energy consumption); and α, β, and γ are the output elasticities of labor, capital, and energy, respectively.

A vital improvement to the CDPF, compared with the original function, was the inclusion of technological change with time, which was noted by Handsaker and Douglas (1938) and Williams (2007). The CDPF of technological change with time is shown as follows:

$$Y(t) = f(K(t), L(t), E(t), T(t)) \tag{3}$$

where *Y(t)* denotes the output, and *T(t)* denotes technological change with time and assumes that technological progress increases at a fixed rate *c*. The formula for the growth of technological progress is as follows:

$$T(t) = Ae^{ct} \tag{4}$$

Therefore, the CDPF formula reported in this paper is as follows:

$$Y(t) = Ae^{ct}K(t)^{\alpha}L(t)^{\beta}E(t)^{\gamma} \tag{5a}$$

where $0 < \alpha, \beta, \gamma < 1$.

3.1.2. Return of scale

In the CDPF, the sum of elasticity values (α, β, γ) represents the degree of the return to scale, which can be interpreted as the response of the production output to a proportionate change in the three inputs (Sircar and Choi, 2009). The first coefficient, α, measures the percentage change in the production output for a percentage increase in the capital input by keeping both the labor and the energy input constant. The coefficient β (or γ) can be interpreted similar to the percentage change in the production output for a percentage increase in the labor (or energy) input by keeping the other two inputs constant. The sum of these three coefficients to unity ($\alpha+\beta+\gamma = 1$) indicates a constant return to scale, which suggests that the production output will double if the inputs double. For ($\alpha + \beta + \gamma > 1$), an increasing return to scale is observed, suggesting that the production output will more than double when the inputs double; similarly, when ($\alpha + \beta + \gamma < 1$), a decreasing return to scale is observed, indicating that the production output will be less than twice as much when the inputs are doubled.

Ye (2007) demonstrated that the construction industry hardly exhibits an economy of scale due to the special production methods for each building product. Moreover, Guna et al. (2007) believed that the economies of scale in construction enterprises mainly originate from production-related activities, but the production-related economies of scale are rarely achieved because the batch standardization of production is almost impossible for the building construction production. According to their statistical results, the ratio of the average output growth rate to the fixed asset growth rate for construction companies is close to 1, indicating that the production of construction companies rarely represent an increasing return to scale. Therefore, in this study, $\alpha + \beta + \gamma = 1$ was set to imply that the production function has a constant return to scale in the construction industry.

3.2. Variables

In this study, four variables, namely, the total output value, capital input, labor input, and energy consumption, were selected to quantify the effects of technological progress on the intensity of energy consumption in the Chinese construction industry. Based on the actual industrial production process, three factors of the abovementioned factors, namely, the capital input, labor input, and energy consumption, are regarded as the input variables. These factors imply the construction industry is capable of producing the output. The total output value is regarded as the output variable in the construction industry.

In formula (5), Y denotes the output.

3.2.1. Total output value (Y)

Similar to previous research, the model adopts an economic indicator, the total output value of the construction industry, as the output variable.

In formula (5), K denotes the capital input, L represents the employee input, and E signifies the energy consumption.

3.2.2. Capital (K)

Since this model attempts to measure the capital that aids in the production of goods, working capital should be excluded because it represents the result and not the cause of the manufacturing process (Cobb and Douglas, 1928). Specifically, fixed capital includes buildings, machinery, equipment, installations, transmission devices, means of transport, and tools, while working capital includes raw materials, goods utilized during the manufacturing process, and finished goods in warehouses, as well as land. Therefore, in this study, the net values of fixed industrial assets (mainly including the monetary worth of all machinery, equipment, and buildings) were selected as the capital input.

3.2.3. Labor (L)

The number of employees employed within the construction industry was used to measure the labor input.

3.2.4. Energy consumption (E)

The total energy consumption of the construction industry was also selected as one of the inputs, and the energy values were converted into ton of standard coal equivalent (TCE). In accordance with the *Chinese Energy Statistics Yearbook*'s terminal direct energy consumption data for the construction industry, the energy consumption in this study included the energy used during both on-site construction and building demolition activities.

Formula (5) can be transformed into formulas (6) and (7) as follows:

$$\alpha + \beta + \gamma = 1 \tag{6}$$

$$\left(\frac{Y}{K}\right)^{\alpha}\left(\frac{Y}{L}\right)^{\beta} = Ae^{ct}\left(\frac{E}{Y}\right)^{\gamma} \tag{7}$$

where $\frac{Y}{K} = y_k$, where y_k denotes the output per capital; $\frac{Y}{L} = y_l$, where y_l denotes the output per laborer; and $\frac{E}{Y} = x_e$, where x_e denotes the energy consumption intensity.

Therefore, formula (7) can be converted into formula (8):

$$Ae^{ct} * x_e^{\gamma} = y_k^{\alpha}*y_l^{\beta} \tag{8}$$

Taking the logarithm on both sides of formula (8), the following is obtained:

$$lnA + ct + \gamma lnx_e(t) = \alpha lny_k(t) + \beta lny_l(t) \tag{9}$$

Taking the derivative on both sides of formula (9), the following is obtained:

$$\gamma\frac{\dot{x_e(t)}}{x_e(t)} = \alpha\frac{\dot{y_k(t)}}{y_k(t)} + \beta\frac{\dot{y_l(t)}}{y_l(t)} - c \tag{10}$$

where $\frac{\dot{x_e(t)}}{x_e(t)}$ denotes the growth rate of $x_e(t)$ (energy intensity), $\frac{\dot{y_k(t)}}{y_k(t)}$ denotes the growth rate of $y_k(t)$ (output per capital), $\frac{\dot{y_l(t)}}{y_l(t)}$ denotes the growth rate of $y_l(t)$ (output per laborer), and $\cdot$ denotes a time derivative.

Formula (10) indicates that an increase in the energy consumption intensity is determined by the growth rate of the output per capital, the growth rate of the output per laborer, the growth rate of technological progress, and the three elasticities. Specifically, the energy intensity will increase when the growth rate of either the output per capital or the output per laborer rises. However, the energy intensity will decrease when the growth rate of technological progress increases.

3.3. Data

The aim of this study was to investigate the effects of technological progress on energy efficiency in the Chinese construction industry spanning the period from 1997 to 2014, given the data availability. The data were obtained from the *China Statistical Yearbook*, *Chinese Construction Industry Statistical Yearbook*, *Chinese Energy Statistical Yearbook,* and *Chinese Science & Technology Yearbook;* all of which are available from the China Statistical Yearbook Database (http://tongji.cnki.net/kns55/index.aspx). Notably, due to differences in the statistical methods, a major change occurred in China's national statistical coverage in 1997; consequently, the energy consumption data in 1997 show an abrupt difference relative to other years (Ma and Stern, 2008), while the data for all of the other years are consistent (Lu et al., 2016). Therefore, in this study, the energy consumption data from 1997 were calculated as the average values of the data between 1996 and 1998. Furthermore, because both the capital input and the total output value from the yearbook are the values at the current price, they needed to be converted into values at a constant price to remove the price change effect.

The steps used to remove the influence of price changes are shown as follows. First, the appropriate price index was determined. Lin and Liu (2015a) recommended the construction and installation engineering price index to calculate the output value at a constant price for the construction industry. Yuan et al. (2009) used the investment of fixed assets price index to calculate the net value of fixed assets at a constant price. Second, the values from the indices were converted into the values based on the 1997 datum. Third, the subsequent value at the constant price can be calculated according to formula (11):

$$v_{coi} = (v_{cui}/p_{oi})*100 \tag{11}$$

where v_{coi} denotes the value calculated at a constant price, and v_{cui} denotes the value at the current price taken directly from the statistics yearbook.

Table 1 shows the values calculated at a constant price. Correspondingly, Fig. 4 illustrates the variable trends over the 18-year period.

4. Results and discussion

4.1. Results

The effect of technological progress on energy consumption in the Chinese construction industry is calculated as follows.

$$\mathrm{Y(t)} = Ae^{ct}K(t)^{\alpha}L(t)^{\beta}E(t)^{\gamma} \tag{5b}$$

After employing a natural logarithm transformation, formula (5) can be expressed in a linear from, as shown in formula (12):

$$\mathrm{lnY = lnA + ct + \alpha lnK + \beta lnL + \gamma lnE} \tag{12}$$

According to $\alpha + \beta + \gamma = 1$, the following is obtained:

$$\beta = 1 - \alpha - \gamma \tag{13}$$

Then, the following is obtained by combining formulas (13) and (14):

$$\mathrm{ln}Y - \mathrm{ln}\,L = \mathrm{ln}A + ct + \alpha(\mathrm{ln}K - \mathrm{ln}L) + \gamma(\mathrm{ln}E - \mathrm{ln}L) + \varepsilon \tag{14}$$

Formula (14) represents a multiple linear regression model, ε denotes an error term. Table 2 shows the variable data needed to estimate the parameters, which have been converted to logarithms.

The Statistical Product and Service Solutions (SPSS) 20.0 software and Stata 15.0 software were employed to estimate the parameters in the CDPF and conduct the different tests. Table 3 shows the estimated coefficients and robust standard errors results, and the estimated multiple linear regression equation is expressed as follows.

$$\mathrm{ln}Y - \mathrm{ln}\,L = 1.311 + 0.087t + 0.165(\mathrm{ln}K - \mathrm{ln}L) + 0.206(\mathrm{ln}E - \mathrm{ln}L) \tag{15}$$

In formula (15), $c = 0.087$, $\alpha = 0.165$, $\gamma = 0.206$, and $\beta = 1 - \alpha - \gamma = 0.629$ $\alpha = 0.165$ indicates that the total output value Y will increase by 0.165% when the capital K increases by 1%. $\beta = 0.629$ indicates that the total output value Y will increase by 0.629% when the labor Y increases by 1%. $\gamma = 0.206$ indicates that the total output value Y will increase by 0.206% when the energy E increases by 1%. Finally, $c = 0.087$ signifies that the growth rate of technological progress is 8.7%.

As shown in Table 3, the adjusted R^2 (0.999), significance, and Robust standard errors indicate that the regression model is good, and the estimation shows that t, (ln$K$-ln$L$), and (ln$E$−ln$L$) each have significant effects on (ln$Y$−ln$L$).

The Breusch-Godfrey LM test for autocorrelation and Breusch-Pagan/Cook-Weisberg test for heteroscedasticity were also conducted. Table 4 and Table 5 show that the data have no autocorrelation and heteroskedasticity.

Furthermore, $VIF_{LnKL} = 4.607$, $VIF_{LnEL} = 8.074$, and $VIF_{LnKL} = 9.736$ show that the multicollinearity test is acceptable because a VIF < 10 means there is no multicollinearity.

According to formulas (15) and (5), the following can be obtained:

$$\mathrm{Y(t)} = e^{1.311}e^{0.087t}K(t)^{0.165}L(t)^{0.629}E(t)^{0.206} \tag{16}$$

Then, the following is derived according to formula (10)

$$0.206\frac{\dot{x_e(t)}}{x_e(t)} = 0.165\frac{\dot{y_k(t)}}{y_k(t)} + 0.629\frac{\dot{y_l(t)}}{y_l(t)} - 0.087 \tag{17}$$

Because the growth rate of technological progress is 8.7%, when the capital input and labor input both remain unchanged, the average growth rate of the total output value per year in the

Table 1
Data of the study's four variables at the constant price.

Year	Total Output Value (TOV) (100 million Yuan)	Net Values of Fixed Assets (NVFA) (100 million Yuan)	Employment Number (EN) (10,000 person)	Energy Consumption (EC) (10,000 TCE)
1997	8869.2906	2168.4464	2101.51	1530
1998	9729.7768	2301.4170	2029.99	1612
1999	10,752.4007	2514.4273	2020.13	1979
2000	11,766.4186	2770.2326	1994.3	2142
2001	14,263.1737	3304.6419	2110.66	2283
2002	17,032.0975	4156.1170	2245.19	2457
2003	20,365.7220	4237.9891	2414.27	2770
2004	23,663.7311	4365.9233	2500.3	3183
2005	27,675.1533	4485.1613	2699.9	3486
2006	32,858.8546	4823.9485	2878.2	3836
2007	38,401.2763	5038.7558	3133.7	4203
2008	41,338.9024	5139.8023	3315	3874
2009	53,148.1538	6007.8681	3672.6	4712
2010	63,327.9695	6339.8922	4160.4	5533
2011	71,099.0050	6370.1429	3852.5	6052
2012	80,422.1291	6791.7721	4267.2	6337
2013	94,400.4418	7243.8625	4528.4	7017
2014	104,086.5106	7478.2542	4537	7520

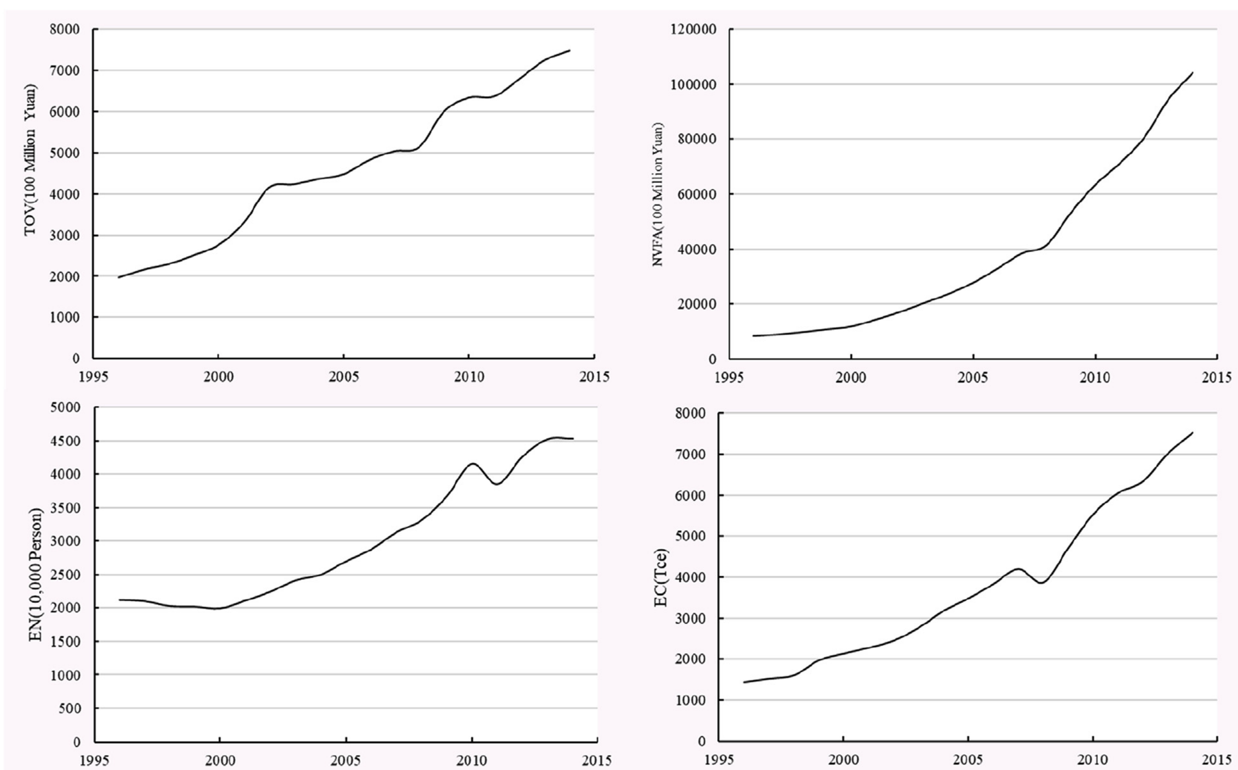

Fig. 4. Trends of the study's four variables at a constant price.

construction industry induced by technological progress can be calculated as follows:

$$\frac{Y_{t+1}-Y_t}{Y_t}=\frac{Ae^{c(t+1)}K^{\alpha}L^{\beta}E^{\gamma}-Ae^{ct}K^{\alpha}L^{\beta}E^{\gamma}}{Ae^{ct}K^{\alpha}L^{\beta}E^{\gamma}}=e^{c}-1 =\left(e^{0.088}-1\right)*100\%=9.1\% \tag{18}$$

Therefore, the growth rate of the total output value per capital and the growth rate of the total output value per labor are both 9.1%. Then, according to formula (17), the following can be obtained:

$$0.206\frac{\dot{x}_e(t)}{x_e(t)}=0.165*0.091+0.629*0.091-0.087 \tag{19}$$

In formula (19), $(0.165*0.091+\ 0.629*0.091)$ denotes that technological progress promotes economic development and thus increases the intensity of energy consumption, while the negative value (-0.087) indicates that technological progress decreases the intensity of energy consumption in the construction industry. Therefore, according to formula (19), $\frac{x_e(t)}{x_e(t)}=-7.1\%$; this negative value (-7.1%) implies that technological progress finally decreases the energy consumption intensity in the construction industry at an

Table 2
Final data for the estimation of the parameters.

	t	LnK - LnL	LnE - LnL	LnY - LnL
1997	1	0.031354838	−0.317061655	1.439938679
1998	2	0.12549415	−0.230555223	1.567160087
1999	3	0.218883204	−0.020570199	1.671967181
2000	4	0.328638166	0.07144686	1.77495648
2001	5	0.44832742	0.078489673	1.910680255
2002	6	0.615791074	0.090150943	2.026309502
2003	7	0.562691917	0.137450356	2.132456228
2004	8	0.557418967	0.241413424	2.247532816
2005	9	0.507559726	0.255540212	2.327320283
2006	10	0.516427689	0.287265058	2.435056156
2007	11	0.474944775	0.293584141	2.50587628
2008	12	0.438556994	0.155829941	2.523346381
2009	13	0.492170107	0.249212588	2.672183511
2010	14	0.42125054	0.28511894	2.722715864
2011	15	0.502899609	0.451666508	2.915351054
2012	16	0.464754024	0.395447596	2.936331502
2013	17	0.469785884	0.4379671	3.037177077
2014	18	0.499733371	0.505300137	3.132956385

Table 3
The coefficients, significance and robust standard errors.

Variables	$\ln Y - \ln L$
$\ln K - \ln L$	0.165**
	(0.0605)
$\ln E - \ln L$	0.206*
	(0.108)
t	0.0869***
	(0.00354)
Constant	1.311***
	(0.0424)
Observations	18
R-squared	0.999

Note: The robust standard errors are in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

Table 4
Breusch-Godfrey LM test for autocorrelation.

chi2	df	Prob > Chi2
0.017	1	0.895

H0: no serial correlation.

Table 5
Breusch-Pagan/Cook-Weisberg test for heteroskedasticity.

Ho: Constant variance
Variables: fitted values of *lnY-lnL*
chi2 (1) = 0.07
Prob > chi2 = 0.7967

average rate of 7.1% per year.

4.2. Roles of technological progress factors in improving energy efficiency

Technological progress has reduced the energy consumption intensity in the Chinese construction industry at an average rate of 7.1% per year over the last 18 years, which is consistent with the findings of most studies that technological progress is a fundamental determinant to energy efficiency improvement in China (Li and Lin, 2017). Based on the results, three factors of technological progress were identified by literature review and expert interviews to use to analyze the roles of technological progress factors in improving energy efficiency.

First, the efficiency of machinery and equipment significantly affects energy efficiency in the construction industry (Yan, 2011). The main sources of energy consumption in the construction industry include machines and equipment, office and living activities at the construction sites, and experiment and maintenance (Chang and Hu, 2010; Weidou and Johansson, 2004). Among them, machinery and equipment (e.g., trucks, loaders, cranes, and pumping and welding machines) are the major energy consumers in the construction industry (Miketa and Mulder, 2005). According to statistical analysis of the Energy Balance Table of China, petroleum products account for more than 60% of all energy types used in the construction industry. The petroleum products are mainly consumed by machinery and equipment, as is the majority of electricity. Therefore, the quantity of machinery and equipment, as well as its energy use efficiency, significantly impact the construction industry's energy consumption.

Fig. 5 shows that the quantity of machinery and equipment in the construction industry is growing, and that the amount of energy consumption is correspondingly increasing. However, according to the statistical data of machine and equipment's energy consumption[3] and the building construction area in the construction industry, the machine and equipment's energy consumption per unit of building construction area can be calculated. The results illustrate a decreasing trend, as shown in Fig. 5. Therefore, although the growth of machinery and equipment increased energy consumption, the machinery and equipment's energy use efficiency reduced the energy intensity; illustrating that the efficiency of machinery and equipment plays a major role in improving energy efficiency in the construction industry.

The second factor of technological progress stems from the changes in the construction industry's energy mix. It is consistent with some previous studies, which reported that the energy structure affects energy efficiency (Lima et al., 2018; Zhou et al., 2017). Fig. 6 indicates eight major energy types used in the construction industry. According to numerous study results in the energy field, the proportion of coal consumption is negatively correlated with energy efficiency (that is, the lower the proportion of coal consumption is, the higher the energy efficiency); on other hand, the growing proportion of high-quality and high-efficiency energy (e.g., electricity) has a positive impact on energy efficiency (Mostafavi et al., 2017; Wang et al., 2016). Fig. 6 further demonstrates that the proportion of coal consumption is gradually decreasing, while the ratio of electricity usage is smoothly increasing. Thus, the proportional changes of both coal and electricity in the construction industry will play an increasing role in improving energy efficiency in the long term.

Third, the capital and human resources from R&D departments in the construction industry are essential for innovating and distributing energy-saving technologies throughout the industry. This echoes previous findings that R&D investment and personnel have positive effects on the development of energy-saving technologies (Alcorta et al., 2014; Song and Oh, 2015). In addition, according to Huang et al. (2019), both indigenous R&D investments and technology spillovers play a role in promoting the technological progress. However, this study did not consider technology spillovers.

[3] According to analysis of the energy balance table of China and interviews with five experts, the energy consumption calculation of machine and equipment includes about 70% electricity and all the petroleum products in the construction industry. The rest of the electricity and the other energy types are mainly used by the office and living activities, experiment and maintenance, and others in the construction industry.

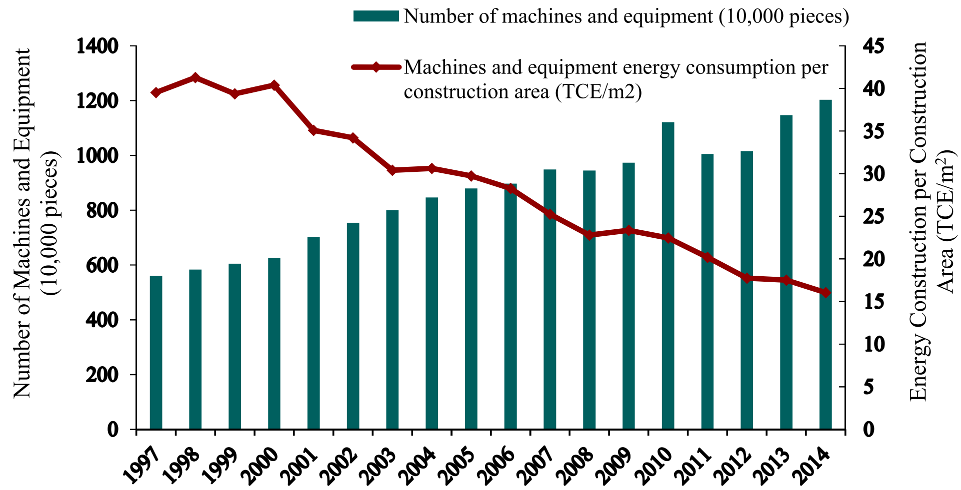

Fig. 5. The amount of machinery and equipment and its energy use efficiency.

First, construction technology and knowledge transfer is complicated and difficult due to cultural barriers and regulatory restrictions (Langford, 2000) because the construction industry is "local" in respect of its regulatory, procurement, political, and social conditions (Ofori, 2003). Second, in the construction industry, such transfer may occur via foreign–local firm joint ventures over a long term (Ofori, 1994). However, Chinese construction companies often take the leading roles in the foreign–local firm joint ventures in China's construction industry. This is because China has developed one of the world's largest and most competitive construction industries, with particular expertise in civil works (Foster et al., 2008). Subcontracting arrangements are also possible vehicles of technology and knowledge transfer, but they are seen as having some limitations because the relationships are often unequal (Devapriya and Ganesan, 2002). Thus, the technological progress in the construction industry mainly results from the activities of local Chinese construction companies; namely, indigenous R&D investments.

Fig. 7 indicates the extremely unstable growth rates of both R&D investment and R&D practitioners in the construction industry over the 18-year study period. The R&D investment shows a small average annual growth rate and R&D personnel exhibits a negative average annual growth rate. Although the construction industry is distinct from the high-tech development industry, the fundamental R&D investments and science and technology practitioner's inputs are indispensable for energy-saving technology development in the construction industry. Therefore, the unstable inputs of both capital and human resources in R&D departments play a limited role in improving the energy efficiency of the China's construction industry.

To verify the significance of effects of the three technological progress factors, an estimation related to the connection of energy efficiency and the three factors was conducted. According to formula (10), the growth rate of energy intensity is influenced by the growth rate of $y_k(t)$, the growth rate of $y_l(t)$, and the growth rate of technological progress. Therefore, the connections between energy efficiency and three factors of technological progress can be illustrated by the following formula:

$$Ee = h\frac{\dot{y_k(t)}}{y_k(t)} + k\frac{\dot{y_l(t)}}{y_l(t)} + lC_1 + mC_2 + nC_3 + \varepsilon \qquad (20)$$

Where Ee denotes the growth rate of energy efficiency (namely, reciprocal of energy intensity); $\frac{\dot{y_k(t)}}{y_k(t)}$ denotes the growth rate of $y_k(t)$; $\frac{\dot{y_l(t)}}{y_l(t)}$ denotes the growth rate of $y_l(t)$; C_1 denotes the growth rate of machinery and equipment efficiency; C_2 denotes the growth rate of the energy structure (namely, the proportion of the sum of

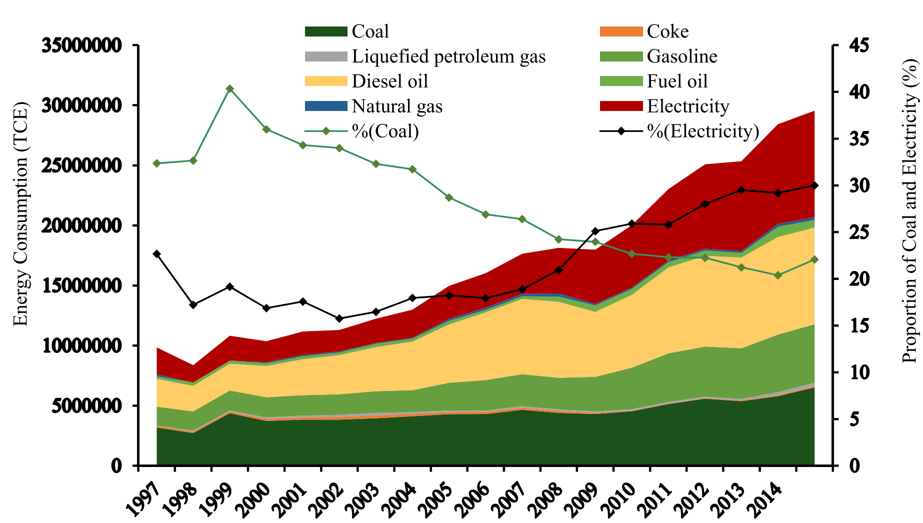

Fig. 6. Different types of energy consumption and energy use percentages in the construction industry.

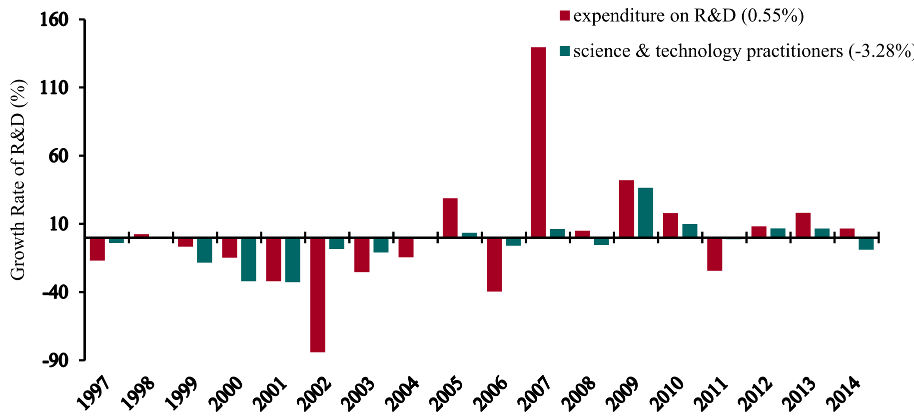

Fig. 7. Growth rates of capital and human resources in R&D departments.

electricity and natural gas into the sum of fossil energy); C_3 denotes the growth rate of R&D; $h, k, l, m,$ and n denote the coefficients; and C_3 denotes the error term. Table 6 shows the estimation results.

Table 7 and Table 8 show that there is no autocorrelation or heteroscedasticity for the data.

For the three factors of technological progress, the estimated results indicated that C_1 and C_2 are significant, while C_3 is not significant. In other words, the positive effects of machinery and equipment efficiency, and energy structure on energy efficiency are significant and are supported. However, the effects of the R&D investment on the energy efficiency are not significant. That could be because there may be no direct relationships between the energy efficiency improvement and the R&D growth rate in the construction industry. However, R&D can affect the improvement in machinery and equipment efficiency, and the energy structure in the construction industry.

4.3. Suggestions

Based on the research results, some suggestions on the machinery and equipment efficiency, as well as the energy structure, are proposed. First, various factors of machinery and equipment efficiency should be identified and well managed. For example, government can focus on phasing out and replacing outdated, high energy-consuming facilities with energy-efficient facilities. In addition, government can set the minimum prefabrication rate for building construction, to encourage the use of prefabricated components on site. The prefabricated components can reduce wasted materials, thus reducing the machinery and equipment energy consumption of waste treatment. Finally, contractors can reduce work delays and arrange the site conditions reasonably to improve machinery and equipment efficiency.

Table 6
Estimation results.

Variables	*Ee*
$\frac{\dot{y_k}(t)}{y_k(t)}$	−0.0802 (0.195)
$\frac{\dot{y_l}(t)}{y_l(t)}$	−0.210 (0.189)
C_1	0.320* (0.156)
C_2	0.327*** (0.0919)
C_3	−0.000455 (0.000314)
Constant	0.0426 (0.0292)
Observations	18
R-squared	0.332

Notes: The robust standard errors are in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

Table 7
Breusch-Godfrey LM test for autocorrelation.

chi2	df	Prob > Chi2
0.019	1	0.890

H0: no serial correlation.

Table 8
Breusch-Pagan/Cook-Weisberg test for heteroskedasticity.

Ho: Constant variance
Variables: fitted values of *Ee* chi2 (1) = 0.35 Prob > chi2 = 0.5540

Second, gradually powering construction machines using electricity instead of diesel is encouraged, to achieve the electrification of construction machinery and equipment. The use of electric-powered construction machines has been increasing, and they will significantly reduce energy consumption and carbon emissions. According to the Director General of the Swedish Energy Agency (SEA), it is a new step for the construction industry, and this trend will lead to the development of the “electric construction site” (CCC news, 2015). For the construction industry, a series of gradual steps could be taken to achieve a higher degree of machinery and equipment electrification, for instance: auxiliary devices to power assist to full hybrid to full electric (He and Jiang, 2018).

Policymakers usually pay attention to energy savings induced by technological progress (Li et al., 2016). Chinese governments have always advocated to achieve energy savings through energy efficiency improvements resulting from technological progress. Related policies also have been promoted as useful avenues to strengthen energy savings of technological progress in China, especially for the construction field. For example, the Ministry of Housing and Urban-Rural Development offers technological progress funding and supports energy efficiency improvements in the construction sector. The specific relative policies are summarized in Appendix A.

5. Conclusions

In this study, a modified model of buildings construction process was first presented to estimate the effects of technological progress on energy efficiency in the construction industry. The research results indicate that technological progress improved energy efficiency by an average of 7.1% per year from 1997 to 2014. Next, the roles of technological progress factors on energy efficiency were analyzed and verified. The first factor, the efficiency of machinery and equipment, plays a major role in reducing energy intensity, and that effect is supported by the statistical data. The second factor, the proportion change of fossil energy and clean energy in the construction industry, will play an increasing role in improving energy efficiency in the long term, and that effect is also supported. The third factor, the R&D inputs of both capital and human resources, plays a limited role in improving energy efficiency, but the effect is not significant. Finally, some recommendations for promoting energy saving in the construction industry were proposed.

The findings of this study contribute to the body of knowledge regarding energy savings in the construction industry. In the building production process, a large amount of construction machinery wastes massive amounts of energy and is a serious source of air pollution. Using electric-powered construction machines instead can reduce energy consumption, carbon dioxide emissions, and noise, creating a cleaner work environment. In addition, the material wasted during the construction process will influence the built environment, and increased use of prefabricated components could help to reduce waste generated on the construction site, thus contributing to cleaner production and the built environment.

There are some limitations to this study. For example, the study's data sample is limited. Thus, future research could focus on enlarging the sample to further explore energy efficiency in the construction industry.

Acknowledgments

The authors would like to thank the China National Key R&D Program (Grant No. 2018YFC0704400) for providing financial support for this project.

Appendix A

Table A
Government policies on energy savings in the construction sector

Department issued	Time issued	Policy
MOHURD	1996	Building Energy Efficiency Technology Policy
	2001	Regulations on the Promotion and Application of New Technologies in the Construction Sector (Ministry of Construction Order No. 109)
	2002	Regulations on Promotion and Application of New Technologies by the Ministry of Construction (Jian Ke (2002) No. 222)
	2006	Catalog of Promotion and Application Technology for Energy-Saving and Land-saving Buildings by the Ministry of Construction (Jian Ke (2006) No. 38)
	2006	National Civil Construction's Design Technical Measures - Energy Saving (Jian Zhi (2006) No. 277)
	2009	Technical Guidelines for Energy Efficiency of Rural Housing in Cold Areas (Trial) (Jian Cun (2009) No. 115)
	2010	Catalog of Technology Promotion of Livable Residential Buildings in Villages and Catalog of Promotion of Energy-Saving Reconstruction of Existing Buildings (Building Research (2010) No. 74)
	2017	Building Energy Conservation and Green Building Development "13th Five-Year Plan" (Jian Ke (2017) No.53) (The energy efficiency of new buildings in urban areas will increase by 20% by 2020.)

Notes: MOHURD is the Ministry of Housing and Urban-Rural Development of the People's Republic of China.

References

Aguilera, R.F., Ripple, R.D., 2012. Technological progress and the availability of European oil and gas resources. Appl. Energy 96, 387–392.
Albino, V., Ardito, L., Dangelico, R.M., Messeni Petruzzelli, A., 2014. Understanding the development trends of low-carbon energy technologies: a patent analysis. Appl. Energy 135, 836–854.
Alcorta, L., Bazilian, M., De Simone, G., Pedersen, A.J.E.E., 2014. Return on investment from industrial energy efficiency: evidence from developing countries, 7 (1), 43–53.
Azari, R., Abbasabadi, N., 2018. Embodied energy of buildings: a review of data, methods, challenges, and research trends. Energy Build. 168, 225–235.
Bentzen, J., 2004. Estimating the rebound effect in US manufacturing energy consumption. Energy Econ. 26 (1), 123–134.
Cannavale, A., Ierardi, L., Hörantner, M., Eperon, G.E., Snaith, H.J., Ayr, U., Martellotta, F., 2017. Improving energy and visual performance in offices using building integrated perovskite-based solar cells: a case study in Southern Italy. Appl. Energy 205, 834–846.
CCC news, 2015. Electrification of Construction Machinery Could Cut Energy Use by 71% – Major Demonstration Project Launched.
Chang, T.-P., Hu, J.-L., 2010. Total-factor energy productivity growth, technical progress, and efficiency change: an empirical study of China. Appl. Energy 87 (10), 3262–3270.
Chen, C., Huang, J., Chang, H., Lei, H., 2019. The effects of indigenous R&D activities on China's energy intensity: a regional perspective. Sci. Total Environ. 689, 1066–1078.
Cobb, C.W., Douglas, P.H., 1928. A theory of production. Am. Econ. Rev. 18, 139–165.
Dasgupta, S., Roy, J., 2015. Understanding technological progress and input price as drivers of energy demand in manufacturing industries in India. Energy Policy 83, 1–13.
Devapriya, K.A.K., Ganesan, S., 2002. Technology transfers through international subcontracting in developing countries. Build. Res. Inf. 30 (3), 171–182.
Dimoudi, A., Tompa, C., 2008. Energy and environmental indicators related to construction of office buildings. Resour. Conserv. Recycl. 53 (1), 86–95.
Dixit, M.K., 2017. Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters. Renew. Sustain. Energy Rev. 79, 390–413.
Dixit, M.K., 2019. Life cycle recurrent embodied energy calculation of buildings: a review. J. Clean. Prod. 209, 731–754.
Fernández, J.E., 2007. Resource consumption of new urban construction in china, 11 (2), 99–115.
Fisher-Vanden, K., Jefferson, G.H., Liu, H., Tao, Q., 2004. What is driving China's decline in energy intensity? Resour. Energy Econ. 26 (1), 77–97.
Foster, V., Butterfield, W., Chen, C., Pushak, N., 2008. Building bridges: China's growing role as infrastructure financier for Sub-Saharan Africa. Int. Bank. Reconstr. Dev. World Bank 1, 1–134.
Geng, G., Wang, Z., Zhao, J., Zhu, N., 2015. Suitability assessment of building energy saving technologies for office buildings in cold areas of China based on an assessment framework. Energy Convers. Manag. 103, 650–664.
Grossmann, D., Galvin, R., Weiss, J., Madlener, R., Hirschl, B., 2016. A methodology for estimating rebound effects in non-residential public service buildings: case study of four buildings in Germany. Energy Build. 111, 455–467.
Guna, K., Li, X., Xiao, H., 2007. New Theory of Construction Industry Economy. Chongqing University Press (in Chinese).
Handsaker, M.L., Douglas, P.H., 1938. The theory of marginal productivity tested by data for manufacturing in victoria, II. Q. J. Econ. 52 (2), 215–250.
Hatirli, S.A., Ozkan, B., Fert, C., 2005. An econometric analysis of energy input–output in Turkish agriculture. Renew. Sustain. Energy Rev. 9 (6), 608–623.
He, X., Jiang, Y., 2018. Review of hybrid electric systems for construction machinery. Autom. ConStruct. 92, 286–296.
Hritonenko, N., Yatsenko, Y., 2013. Modeling of Technological Change.
Hu, Z., Hu, Z., 2013. Production function with electricity consumption and its applications. Energy Econ. 39, 313–321.
Huang, J., Du, D., Hao, Y., 2017a. The driving forces of the change in China's energy intensity: an empirical research using DEA-Malmquist and spatial panel estimations. Econ. Modell. 65, 41–50.
Huang, J., Du, D., Tao, Q., 2017b. An analysis of technological factors and energy intensity in China. Energy Policy 109, 1–9.
Huang, J., Hao, Y., Lei, H., 2018. Indigenous versus foreign innovation and energy intensity in China. Renew. Sustain. Energy Rev. 81, 1721–1729.
Huang, J., Cai, X., Huang, S., Tian, S., Lei, H., 2019. Technological factors and total factor productivity in China: evidence based on a panel threshold model. China Econ. Rev. 54, 271–285.
Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A., 2013. Operational vs. embodied emissions in buildings—a review of current trends. Energy Build. 66, 232–245.
Jian Ke, 2002. MOHURD, Regulations on Promotion and Application of New Technologies by the Ministry of Construction. No. 222. http://www.mohurd.gov.cn/wjfb/200611/t20061101_158410.html.
Jian Ke, 2006. MOHURD, Catalog of Promotion and Application Technology for Energy-Saving and Land-saving Buildings by the Ministry of Construction. No. 38. http://www.mohurd.gov.cn/wjfb/200611/t20061101_158492.html.
Jian Zhi, 2006. MOHURD, National Civil Construction's Design Technical Measures -

Energy Saving. No. 277. http://www.mohurd.gov.cn/wjfb/200612/t20061212_158193.html.

Jian Cun, 2009. MOHURD, Technical Guidelines for Energy Efficiency of Rural Housing in Cold Areas (Trial). No. 115. http://www.mohurd.gov.cn/wjfb/200907/t20090707_192137.html.

Building Research, 2010. MOHURD, Catalog of Technology Promotion of Livable Residential Buildings in Villages and Catalog of Promotion of Energy-Saving Reconstruction of Existing Buildings. No. 74. http://www.mohurd.gov.cn/wjfb/201006/t20100607_201278.html.

Jian Ke, 2017. MOHURD, Building Energy Conservation and Green Building Development "13th Five-Year Plan". No. 53. http://www.mohurd.gov.cn/wjfb/201703/t20170314_230978.html.

Karali, N., Park, W.Y., McNeil, M., 2017. Modeling technological change and its impact on energy savings in the U.S. iron and steel sector. Appl. Energy 202, 447–458.

Langford, D., 2000. The influence of culture on internationalisation of construction. In: Proceedings of the 2nd International Conference on Construction in Developing Countries. University of Botswana, pp. 12–21.

Li, K., Lin, B., 2014. The nonlinear impacts of industrial structure on China's energy intensity. Energy 69, 258–265.

Li, K., Lin, B., 2017. An application of a double bootstrap to investigate the effects of technological progress on total-factor energy consumption performance in China. Energy 128, 575–585.

Li, Y., Sun, L., Feng, T., Zhu, C., 2013. How to reduce energy intensity in China: a regional comparison perspective. Energy Policy 61, 513–522.

Li, K., Zhang, N., Liu, Y., 2016. The energy rebound effects across China's industrial sectors: an output distance function approach. Appl. Energy 184, 1165–1175.

Lima, L.P.d., Ribeiro, G.B.d.D., Perez, R., 2018. The energy mix and energy efficiency analysis for Brazilian dairy industry. J. Clean. Prod. 181, 209–216.

Lin, B., Li, J., 2014. The rebound effect for heavy industry: empirical evidence from China. Energy Policy 74, 589–599.

Lin, B., Liu, H., 2015a. CO2 mitigation potential in China's building construction industry: a comparison of energy performance. Build. Environ. 94, 239–251.

Lin, B., Liu, H., 2015b. A study on the energy rebound effect of China's residential building energy efficiency. Energy Build. 86, 608–618.

Lin, B., Tian, P., 2016. The energy rebound effect in China's light industry: a translog cost function approach. J. Clean. Prod. 112, 2793–2801.

Lin, B., Zhang, G., 2013. Estimates of electricity saving potential in Chinese nonferrous metals industry. Energy Policy 60, 558–568.

Liu, H., Lin, B., 2016. Incorporating energy rebound effect in technological advancement and green building construction: a case study of China. Energy Build. 129, 150–161.

Lu, Y., Cui, P., Li, D., 2016. Carbon emissions and policies in China's building and construction industry: evidence from 1994 to 2012. Build. Environ. 95, 94–103.

Ma, C., Stern, D.I., 2008. China's changing energy intensity trend: a decomposition analysis. Energy Econ. 30 (3), 1037–1053.

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard Rasmussen, F., Houlihan Wiberg, A., Potting, J., 2018. Design and construction strategies for reducing embodied impacts from buildings – case study analysis. Energy Build. 166, 35–47.

Menyhart, K., Krarti, M., 2017. Potential energy savings from deployment of Dynamic Insulation Materials for US residential buildings. Build. Environ. 114, 203–218.

Miketa, A., Mulder, P., 2005. Energy productivity across developed and developing countries in 10 manufacturing sectors: patterns of growth and convergence. Energy Econ. 27 (3), 429–453.

Mobtaker, H.G., Keyhani, A., Mohammadi, A., Rafiee, S., Akram, A., 2010. Sensitivity analysis of energy inputs for barley production in Hamedan Province of Iran. Agric. Ecosyst. Environ. 137 (3), 367–372.

Mostafavi, N., Farzinmoghadam, M., Hoque, S., 2017. Urban residential energy consumption modeling in the integrated urban metabolism analysis tool (IUMAT). Build. Environ. 114, 429–444.

Noailly, J., 2012. Improving the energy efficiency of buildings: the impact of environmental policy on technological innovation. Energy Econ. 34 (3), 795–806.

Ofori, G., 1994. Construction industry development: role of technology transfer. Constr. Manag. Econ. 12, 379–392.

Ofori, G., 2003. Frameworks for analyzing international construction. Constr. Manag. Econ. 21 (4), 379–391.

Ouyang, X., Lin, B., 2015. Analyzing energy savings potential of the Chinese building materials industry under different economic growth scenarios. Energy Build. 109, 316–327.

Patterson, M.G., 1996. What is energy efficiency? concepts, indicators and methodological issues. Energy Policy 24 (5), 377–390.

Proskuryakova, L., Kovalev, A., 2015. Measuring energy efficiency: Is energy intensity a good evidence base? Applied Energy 138, 450–459.

Rafiee, S., Mousavi Avval, S.H., Mohammadi, A., 2010. Modeling and sensitivity analysis of energy inputs for apple production in Iran. Energy 35 (8), 3301–3306.

Sircar, S., Choi, J., 2009. A Study of the Impact of Information Technology on Firm Performance: A Flexible Production Function Approach.

Song, C., Oh, W., 2015. Determinants of innovation in energy intensive industry and implications for energy policy. Energy Policy 81, 122–130.

Skyscrapercenter, 2018. The Global Tall Building Picture: Impact of 2018.

Voigt, S., De Cian, E., Schymura, M., Verdolini, E., 2014. Energy intensity developments in 40 major economies: structural change or technology improvement? Energy Econ. 41, 47–62.

Wang, S., Fang, C., Guan, X., Pang, B., Ma, H., 2014. Urbanisation, energy consumption, and carbon dioxide emissions in China: a panel data analysis of China's provinces. Appl. Energy 136, 738–749.

Wang, H., Fan, Z., Zhang, R., 2016. Empirical analysis on the relationship between energy efficiency and energy structure of VAR. J. Ind. Technol. Econ. 35, 128–134 (in Chinese).

Weidou, N., Johansson, T.B., 2004. Energy for sustainable development in China. Energy Policy 32 (10), 1225–1229.

Williams, J., 2007. Professor Douglas Production Function.

Xu, B., Lin, B., 2016. Assessing CO2 emissions in China's iron and steel industry: a dynamic vector autoregression model. Appl. Energy 161, 375–386.

Yan, Y., 2011. Research of Energy Consumption and CO2 Emission of Buildings in Zhenjiang Province Based on Life Cycle Assessment. Zhejiang University.

Ye, Y., 2007. Analysis of technical progress for China's construction industry. China POPULATION. Resour. Environ. 17, 44–49 (in Chinese).

Yuan, C., Liu, S., Wu, J., 2009. Research on energy-saving effect of technological progress based on Cobb–Douglas production function. Energy Policy 37 (8), 2842–2846.

Zeng, R., Chini, A., 2017. A review of research on embodied energy of buildings using bibliometric analysis. Energy Build. 155, 172–184.

Zha, D., Zhou, D., 2014. The elasticity of substitution and the way of nesting CES production function with emphasis on energy input. Appl. Energy 130, 793–798.

Zha, D., Kavuri, A.S., Si, S., 2017. Energy biased technology change: focused on Chinese energy-intensive industries. Appl. Energy 190, 1081–1089.

Zhao, D., Lu, X., Fan, T., Wu, Y.S., Lou, L., Wang, Q., Fan, J., Yang, R., 2018. Personal thermal management using portable thermoelectrics for potential building energy saving. Appl. Energy 218, 282–291.

Zhou, D.Q., Meng, F.Y., Bai, Y., Cai, S.Q., 2017. Energy efficiency and congestion assessment with energy mix effect: the case of APEC countries. J. Clean. Prod. 142, 819–828.